DOE/NASA CONTRACTOR REPORT

DOE/NASA CR-161339

OUTDOOR TEST FOR THERMAL PERFORMANCE EVALUATION OF THE OWENS-ILLINOIS SUNPAK SEC-601 (AIR) SOLAR COLLECTOR

Prepared by

Wyle Laboratories
Solar Energy Systems Division
Huntsville, Alabama 35805

Under subcontract with IBM Corp., Federal Systems Division, Huntsville, Ala. 35805

Contract NAS8-32036

National Aeronautics and Space Administration
George C. Marshall Space Flight Center, Alabama 35812

For the U. S. Department of Energy

(NASA-CR-161339) OUTDOOR TEST FOR THERMAL PERFORMANCE EVALUATION OF THE OWENS-ILLINOIS SUNPACK SEC-601 (AIR) SOLAR COLLECTOR (Wyle Labs., Inc.) 28 p HC A03/MF A01 CSCL 10A

N80-16492

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1.0 PURPOSE

The purpose of this document is to present the test procedures used and the test results obtained during the performance of an evaluation test program on the Owens-Illinois Sunpak, model SEC-601, air solar collector under natural outdoor weather conditions. All testing activities were performed on a single module installed on the MSFC Solar House. The test was performed and the data evaluated according to the methods provided in Reference 2.1 as applicable to outdoor testing of solar collectors.

2.0 REFERENCES

2.1	ASHRAE 93-77	Method of Testing to Determine the Thermal Performance of Solar Collectors
2.2	NBSIR 78-1305A	Provisional Flat Plate Solar Collector Testing Procedures: First Revision
2.3	DOE/NASA CR-150860	Qualification Test and Analysis Report - Solar Collectors (Owens-Illinois SEC-601 Sunpak Collector)

3.0 COLLECTOR DESCRIPTION

Manufacturer:	Owens-Illinois	
Manufacturer's Address:	P. O. Box 1035 Toledo, Ohio 43666	
Model Number:	Sunpak SEC-601	
Type:	Evacuated Tube	
Working Fluid:	Air	
Gross Collector Area, Ft^2:	104.96	
Overall External Dimensions:	Width, inches Length, inches	103.1 146.6
Collector Glazing:	Evacuated Tube	
Weight:	Total Module, lbs. Without Tubes, lbs.	338 118
Diffuse Reflector	Certainteed double 4" siding, No. 002-13	

4.0 SUMMARY

This test program was conducted to evaluate the performance of an Owens-Illinois Sunpak SEC-601 air, evacuated tube solar collector under outdoor conditions. The module tested, shown schematically in Figure 1, was one of four modules constituting a solar heating system at the MSFC Solar House. A schematic of the complete test loop is shown in Figure 2. The array was operated and monitored over a period of approximately two months (August and September 1979) to provide sufficient data under ideal testing conditions to insure that the data presented is suitable for the purpose intended. The test conditions and data obtained from selected days during the test program are listed in Table I for the thermal performance test, and are presented graphically in Figures 3 through 6. Table II contains the data and results obtained in determining the incident angle modifier for the Sunpak SEC-601. The consolidated incident angle modifier data from three days is shown in Figure 7. A time constant test was performed to determine the transient effects of changing solar flux. The results of the time constant test are presented in Figure 8.

The only common ground for comparing overall collector performance should be the "all day efficiency" rather than $F_R \alpha \tau$. No standard practice has been established, but each collector should be evaluated for space heating, domestic hot water and solar cooling or process heat applications at a nominal location. This would assist the solar designer in choosing the most efficient collector for a particular application. Evacuated tube collectors are effective for solar cooling applications; therefore, according to the procedure in NBSIR 78-1305A, an all day efficiency for the Sunpak SEC-601 was calculated for a typical solar cooling application. The selected site dependent data in conjunction with test results used in this determination are shown in Table III.

The specified diffuse reflector material, Alcoa roofing coated with Alcoa bone white #K2028-30 (fluorocarbon) was not available. A substitute material, Certainteed double 4" siding No. 002-13, was used for these tests. This white vinyl material reportedly has a slightly better reflectance but does not have the same surface shape as the specified material. It is not expected that this change in the diffuse reflector material caused a significant change in the collector performance, but due to the unavailability of the specified material, this was not verified. Contractor data reported in Reference 2.3 is shown, however, for comparison of performance parameters.

5.0 TEST CONDITIONS AND TEST EQUIPMENT

5.1 Ambient Conditions

Unless otherwise specified herein, all tests were performed at ambient conditions existing at the MSFC Solar House Test Facility at the time of the tests.

5.2 Instrumentation and Equipment

All test equipment and instrumentation used in the performance of this test program comply with the requirements of MSFC-MMI-5300.4C, Metrology and Calibration. Instrumentation locations on the test loop and collector are depicted in Figure 2. A listing of the equipment used in each test follows:

Apparatus	Manufacturer/Model	Range/Accuracy
Thermocouples	MSFC Supplied	0 - 500°F $\pm$ 0.5°F
Pyranometer	Eppley - PSP	0-800 BTU/Ft^2-Hr $\pm$ 3%
Shadowband Pyranometer	Eppley - PSP	0-900 BTU/Ft^2-Hr $\pm$ 3%
Air Loop	MSFC Supplied	N/A
Data Logger	Model 2240A, John Fluke Company	1-30MV $\pm$ .01%
Flowmeter	Kurz Instruments/ Model 430/435	0 - 1250 FPM $\pm$ 2%

The PSP pyranometers were calibrated by the manufacturer.

6.0 TEST REQUIREMENTS AND PROCEDURES

6.1 Collector Thermal Efficiency Test

6.1.1 Test Requirements

Thermal performance data from the Sunpak Model SEC-601 air collector shall be obtained utilizing the MSFC air test loop at the MSFC Solar House Test Facility. The collector shall be mounted on the south, facing 45° sloped roof of the Solar House, with a roof covering of Alcoa Bone White, #K2028-30 (fluorocarbon) diffuse radiation material, or equivalent. The following data shall be recorded of test variables and conditions.

1. Ambient Air temperature.
2. Collector inlet air temperature.
3. Collector outlet air temperature.
4. Collector air flow rate.
5. Total insolation.
6. Diffuse component of insolation.

Thermal performance evaluation data shall be obtained at inlet temperatures of approximately 0, 70, 90 and 110°F above the ambient temperature at an air flow rate of 2 CFM per Ft^2 of collector. The efficiency curve shall be established by "data points" taken at one minute intervals near solar noon that represent efficiency values determined by integrating the data over a time period equal to the time constant or five minutes, whichever is larger. The integrated value of incident solar energy will be divided into the integrated value of energy obtained from the collector to obtain an averaged thermal efficiency.

6.1.2 Procedure

1. Assure that all insulated ducts are tightly sealed.
2. Initiate operation of the data acquisition system to record data at one minute intervals between 11:00 A.M. and 1:00 P.M. solar time and check to verify that all necessary data channels are operational.
3. Establish the proper flow rate and inlet temperature for each test designation.
4. Monitor the test parameters by using the data logger printout at the test site.
5. Upon completion of testing, save the printout as a record.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.1 Collector Thermal Efficiency Test (Continued)

6.1.3 Test Results

The results obtained during these tests are contained in Table I and in Figure 3 for thermal performance data. The calculated thermal efficiency is compared with the manufacturer's predicted performance in Figure 4 for an inlet temperature equal to the ambient. Figures 5 and 6 show collector thermal efficiency at recorded insolation levels as a function of time of day for two different days, with the inlet temperature equal to the ambient.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.2 Incident Angle Modifier Test

6.2.1 Requirements

Due to the collector's being permanently mounted at the 45° slope of the MSFC Solar House roof, the collector incident angle modifier shall be determined from collector efficiency data when the direction of incident solar radiation is approximately 15, 30, 45, 60 and 67.5 degrees with respect to 0° at solar noon. Since these tests are being performed at outdoor conditions, the inlet air temperature should be maintained as close as practical to ambient (± 2°F). The test should be conducted on a clear day with a wind speed of less than 5 MPH. The efficiency values are determined in five pairs, where each pair includes a value of efficiency early in the day and a second value late in the day. The following data shall be recorded at two minute intervals from 7:30 A.M. to 4:30 P.M. solar time on a clear test day.

1. Ambient air temperature.

2. Collector inlet air temperature.

3. Collector outlet air temperature.

4. Collector air flow rate.

5. Total insolation.

6. Diffuse component of insolation.

6.2.2 Procedure

1. Assure that all insulated ducts are tightly sealed.

2. Initiate operation of the data acquisition system to record data at two minute intervals between 7:30 A.M. and 4:30 P.M. solar time and check to verify that all necessary data channels are operational.

3. Establish a flow rate of 2 CFM per Ft^2 of collector at an inlet temperature approximately equal to ambient.

4. Monitor the test parameters by using the data logger printout at the test site.

5. Upon completion of testing, save the printout as a record.

6.2.3 Test Results

Incident angle modifier data was taken on three clear days as is shown in Table II. The average of the data from those three days is depicted graphically in Figure 7.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.3 Time Constant Test

6.3.1 Test Requirements

In accordance with ASHRAE 93-77, the time constant test shall be conducted by abruptly reducing the solar flux to zero. This will be done with the inlet air temperature as close to ambient as practical ($\pm 2^{o}F$), with an air flow rate of 2 CFM per ft^2 of collector. The differential temperature across the collector shall be recorded to determine the time required to reach the condition of

$$\frac{T_{f,e,\tau} - T_{f,i}}{T_{f,e,ini} - T_{f,i}} = .368$$

where $T_{f,e,\tau}$ = Outlet air temperature at time τ

$T_{f,e,ini}$ = Initial outlet temperature

$T_{f,i}$ = Inlet air temperature

The following data shall be recorded during the test.

1. Ambient air temperature.
2. Collector inlet air temperature.
3. Collector outlet air temperature.
4. Collector air flow rate.
5. Total insolation at initiation of test.
6. Time from initiation to completion of test at one minute intervals.

6.3.2 Procedure

1. Initiate operation of the data acquisition system to record data at one minute intervals and check to verify that all necessary data channels are operational.
2. Establish a flow rate of 2 CFM per ft^2 of collector at an inlet temperature approximately equal to ambient.
3. Assure that the flux level is at least 250 $BTU/Hr\text{-}Ft^2$ and is not fluctuating.
4. Assure that test conditions have stabilized.

6.0 TEST REQUIREMENTS AND PROCEDURES (Continued)

6.3 Time Constant Test (Continued)

6.3.2 Procedure (Continued)

5. Reduce the solar flux to zero by abruptly shading the collector from the sun. Mark on the data acquisition system printout the moment when the collector is shaded.

6. Monitor and record the differential temperature across the collector until the ratio of $\frac{T_{f,e,\tau} - T_{f,i}}{T_{f,e,ini} - T_{f,i}}$ is less than 0.30.

6.3.3 Test Results

The results obtained during this test are shown in Figure 8.

7.0 ANALYSIS

7.1 Thermal Performance Test

The analysis of data contained in this report is consistent with the procedures of References 2.1 and 2.2. The thermal efficiency of the Sunpak SEC-601 determined from test data contained in Table I is given by the following equation:

$$\eta = 0.423 - 0.160 \left(\frac{T_i - T_a}{I}\right)$$

The calculated values of efficiency were determined at sixty second intervals near solar noon and averaged over a fifteen minute period in which the test conditions remained in a quasi-steady state. Each fifteen minute average constitutes one data point shown graphically in Figure 3. Due to the excellent insulative properties of the evacuated tube and considerable data scatter, the best curve fit is a first order polynomial of the form:

$$\eta = a_o + a_1 \tau$$

where:

$$\tau = (T_i - T_a)/I$$

The coefficients were determined to be

a_0 0.423

a_1 -0.160

for a flow rate of 2 CFM/Ft^2 of collector.

7.0 ANALYSIS (Continued)

7.2 Incident Angle Modifier Test

Two methods are proposed by ASHRAE 93-77 for incident angle modifier tests. For the MSFC Solar House Test Facility only method 2 (testing outside using a permanent test rack) is applicable. Efficiency data was determined when the direction of incident solar radiation was approximately 15, 30, 45, 60, and 67.5 degrees with respect to 0^{o} at solar noon on three clear days.

According to 93-77, the incident angle modifier is defined as

$$K\alpha\tau = \frac{\eta}{F_R(\tau\alpha)\,n} \qquad (1)$$

where η = efficiency at incident angle.

$F_R(\alpha\tau)\,n$ = Intercept of efficiency curve at normal incident angle = .423

For equation (1) to be applicable, the inlet air temperature must be controlled to within $\pm$ 2^{o}F of the ambient air temperature. In cases where the inlet air temperature cannot be controlled to within $\pm$ 2^{o}F, the following equation must be used to evaluate the incident angle modifier.

$$K\alpha\tau = \frac{\eta + F_R U_L \dfrac{T_{f,i} - T_a}{I}}{F_R(\alpha\tau)\,n} \qquad (2)$$

where:

$F_R U_L$ is the negative of the slope determined from the thermal efficiency curve.

The inlet air temperatures were all within $\pm$ 2^{o}F of ambient air temperature. Hence, equation (1) was used for evaluation.

$$K\alpha\tau = \frac{\eta}{F_R(\alpha\tau)\,n}$$

The results of this computation are shown on Table II and plotted against incident angle in Figure 7.

The purpose of the incident angle modifier is to allow a designer or analyst to predict the total daily energy output from the collector, as the sun tracks from east to west. Most collectors are more efficient at normal incidence than at other angles, but some are even more efficient at angles other than normal. The only common ground for comparing collectors should be the "all day efficiency" rather than $F_R\alpha\tau$. However, the prospective application of the collector also influences the value of "all day efficiency." That is, for low temperature applications such as space heating or domestic hot water, a typical flat plate collector may have an all day efficiency of 40%, but for solar cooling applications the all day efficiency might be 20%. Therefore, criteria should be established to

7.0 ANALYSIS (Continued)

7.2 Incident Angle Modifier Test (Continued)

rate each collector for space heating, domestic hot water, and solar cooling at a nominal location, because efficiencies are also dependent on outdoor ambient temperatures.

Evacuated tubes are effective for solar cooling applications; therefore, according to the procedure in NBSIR 78-1305A, the all day efficiency of the Sunpak SEC-601 collector is 35.9 per cent for a typical solar cooling application where T_{in} is approximately $100^{o}F$ above ambient. The selected site dependent data in conjunction with test data used in these determinations is shown in Table III. No standard criteria has been established for "all day efficiency" and these calculations are dependent on system operating parameters, site data, time of year and daily weather. Therefore, the above information should be viewed as interesting but not conclusive.

7.0 ANALYSIS (Continued)

7.3 Time Constant Test

Two methods are proposed by ASHRAE 93-77 for conducting a time constant test; however, due to facility limitations, the first method was used. This method consisted of shading the collector and maintaining a constant flow rate and inlet temperature while obtaining data.

According to the definition of time constant given in 93-77, it is the time required for the ratio of the differential temperature at time τ to the initial differential temperature to reach .368, when solar insolation is reduced to zero. It can be expressed as:

$$\frac{T_{f,e,\tau} - T_{f,i}}{T_{f,e,ini} - T_{f,i}} = .368 \qquad (1)$$

If the inlet liquid temperature cannot be controlled to equal the ambient air temperature, then the following equation must be used.

$$\frac{F_R U_L\ (T_{f,i} - T_a) + \frac{\dot{m}C_p}{A_g}\ (T_{f,e,\tau} - T_{f,i})}{F_R U_L\ (T_{f,i} - T_a) + \frac{\dot{m}C_p}{A_g}\ (T_{f,e,ini} - T_{f,i})} = .368 \qquad (2)$$

where:

$T_{f,e,\tau}$	Exit liquid temperature at time τ
$T_{f,i}$	Inlet liquid temperature
$T_{f,e,ini}$	Initial exit liquid temperature
$\dot{m}$	Liquid mass flow rate, lb/hr
Cp	Specific heat of liquid, BTU/lb·°F
Ag	Gross collector area, ft^2
$F_R U_L$	Negative of the slope determined from the thermal efficiency curve

The inlet temperature was maintained within $\pm$ 2°F of the ambient, hence equation (1) was used for evaluation. From Figure 8, the time constant was determined to be 15 minutes and 36 seconds.

TABLE I

THERMAL PERFORMANCE TEST DATA FOR THE SUNPAK SEC-601 AIR COLLECTOR

Ambient Air Temp. (T_a), °F	71.4	75.0	73.5	86.8	90.8	87.0	88.8	92.0	83.7	89.7	89.8
Fluid Inlet Temp. (T_i), °F	73.4	75.3	74.6	154.6	163.9	165.9	171.5	195.2	134.6	176.3	200.2
Fluid Outlet Temp. (T_e), °F	133.1	141.2	139.5	212.1	221.0	226.9	213.8	246.1	164.9	233.7	255.7
Differential Fluid Temp. (ΔT), °F	59.7	65.9	64.9	57.5	57.1	61.0	42.3	50.9	30.3	57.4	55.5
Total Solar Flux (I), BTU/Hr·Ft^2	325.6	328.3	327.5	300.2	295.1	265.9	213.5	273.6	170.8	278.3	269.8
% of Diffuse Flux	12	20	15	31	30	40	35	30	30	30	30
Flow Rate, CFM/Ft^2 of Collector	2.05	2.00	1.93	1.78	1.78	1.54	1.65	1.55	2.00	1.54	1.50
$(T_i - T_a)/I$ °F·Hr·Ft^2/BTU	.006	.001	.003	.226	.248	.297	.387	.377	.298	.311	.409
Efficiency (η), %	41.2	43.6	42.2	37.3	37.8	39.2	36.0	35.4	37.0	34.6	34.0

TABLE II

INCIDENT ANGLE MODIFIER DATA

Date	Angle °	η Coll. Eff.	$K\alpha\tau$
8/16/79	0	43.6	1.000
"	15	44.0	1.009
"	30	45.3	1.039
"	45	48.9	1.122
"	60	57.6	1.321
"	67.5	50.9	1.167
9/15/79	0	42.2	1.000
"	15	42.8	1.014
"	30	44.2	1.047
"	45	48.5	1.149
"	60	54.8	1.298
"	67.5	51.5	1.220
9/23/79	0	41.2	1.000
"	15	41.4	1.007
"	30	42.7	1.037
"	45	47.2	1.147
"	60	56.0	1.361
"	67.5	50.0	1.215

Average Over 3 Days

Angle °	$K\alpha\tau$
0	1.000
15	1.010
30	1.041
45	1.139
60	1.327
67.5	1.200

TABLE III

SUNPAK MODEL SEC-601 EVACUATED TUBE AIR COLLECTOR CALCULATED ALL DAY EFFICIENCY

CALCULATION STEPS	HOUR OF THE DAY, SOLAR TIME												DAILY TOTAL
	6-7	7-8	8-9	9-10	10-11	11-12	12-1	1-2	2-3	3-4	4-5	5-6	
1. Inlet fluid temp. to collector, $t_{f,i}$ (°F)	185	185	185	185	188	190	193	197	200	200	200	200	
2. Ambient air temp., t_a (°F)	73	74	79	82	86	90	92	93	94	94	92	90	
3. Incident radiation on collector plane, I_T (Table A2, ASHRAE 93-77) (BTU/Hr)	6	60	132	197	249	281	292	281	249	197	132	60	2144
3a. $T_{fi}-T_a/I_T$	18.0	1.85	.80	.52	.41	.36	.35	.37	.43	.54	.82	1.8	
4. Collector thermal efficiency at normal incidence, determined in accordance with Sections 8.3.2 and 8.5 of ASHRAE 93-77 and using data from Lines 1, 2 and 3		.125*	.291	.338	.356	.364	.365	.362	.352	.334	.288	0	
5. Incident angle between direct solar beam and outward drawn normal to collector plane, θ d	90	75	60	45	30	15	15	30	45	60	75	90	
6. Incident angle modifier, determined in accordance with Sections 8.3.3 & 8.6 of ASHRAE 93-77 and using the value of θ from Line 5	0	1.040*	1.327	1.139	1.041	1.010	1.010	1.041	1.139	1.327	1.040*	0	
7. Energy output from collector [Line 3 x Line 4 x Line 6] (BTU/Hr)		7.8	50.97	75.84	92.28	103.30	107.65	105.89	99.83	87.31	39.54		770.41
8. Collector thermal efficiency, Line 7/Line 3													.359

Example: 32°N Lat.
42° Tilt
Avg.- Clear Skies

* Estimated or extrapolated values.

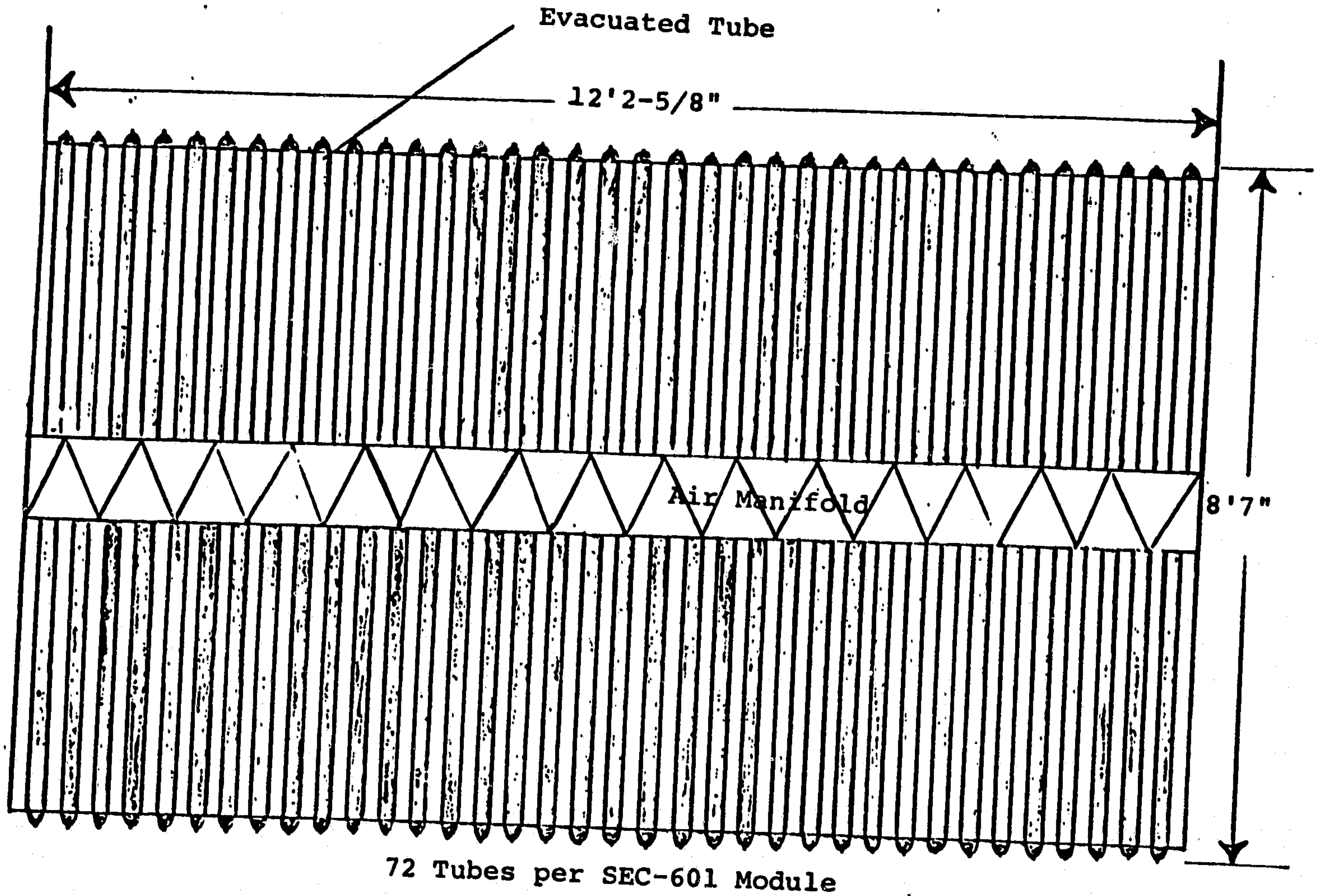

Figure 1. Owens-Illinois Model SEC-601 Sunpak Air Collector

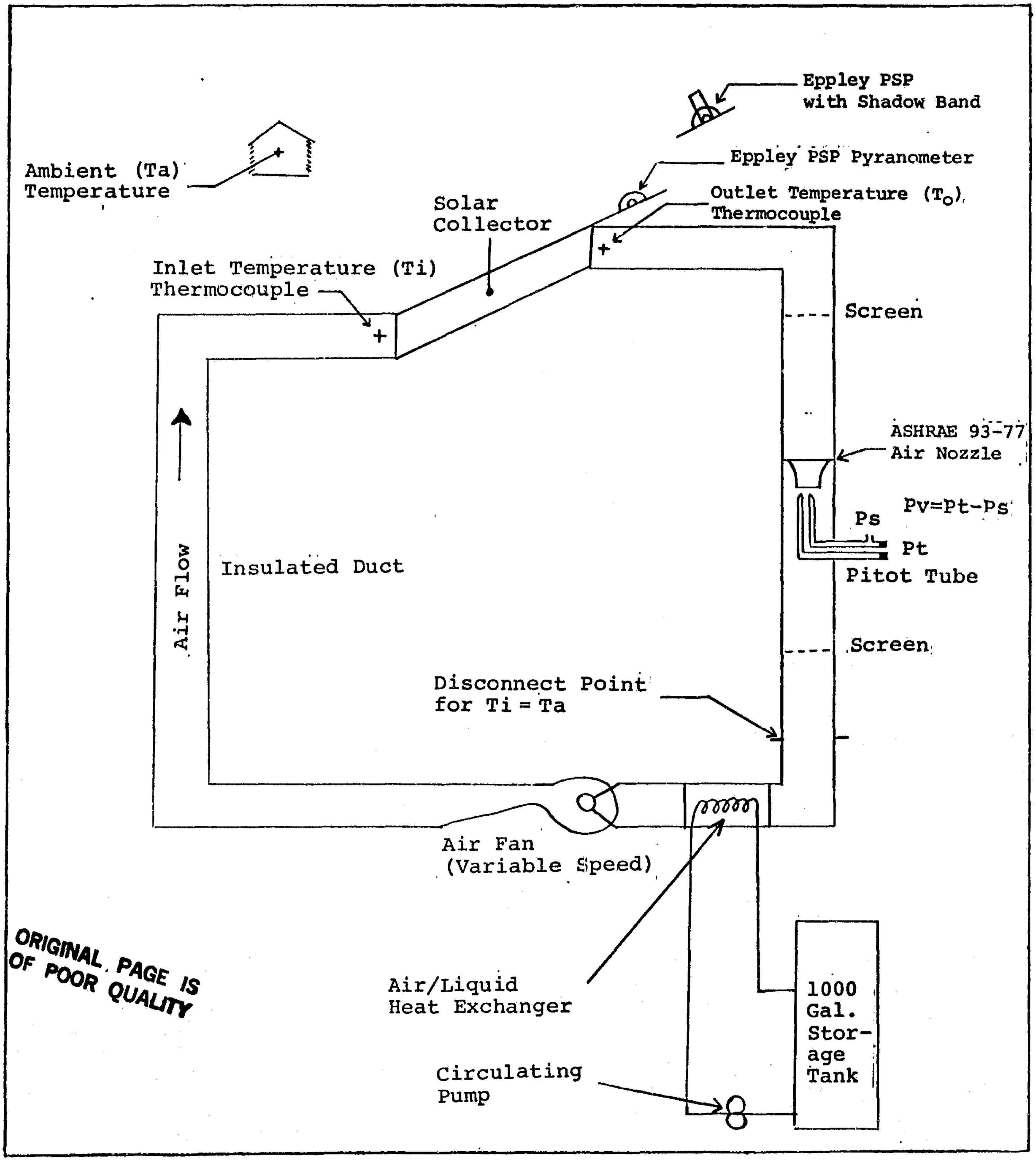

Figure 2. Loop Schematic of the Owens-Illinois Sunpak Model SEC-601 Air Collector

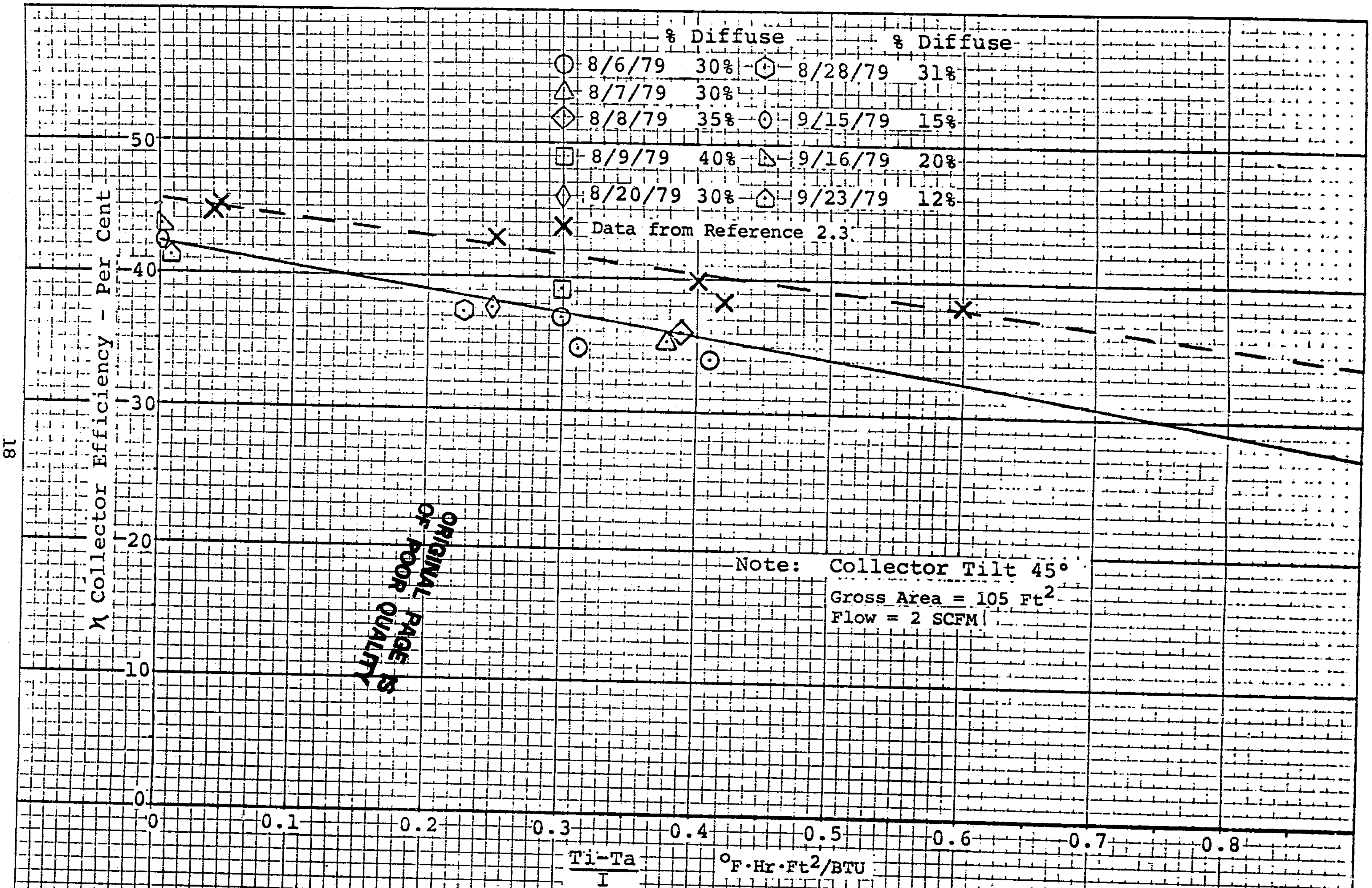

Figure 3. Thermal Efficiency of the Owens-Illinois Sunpak SEC-601 Evacuated Tube Air Collector

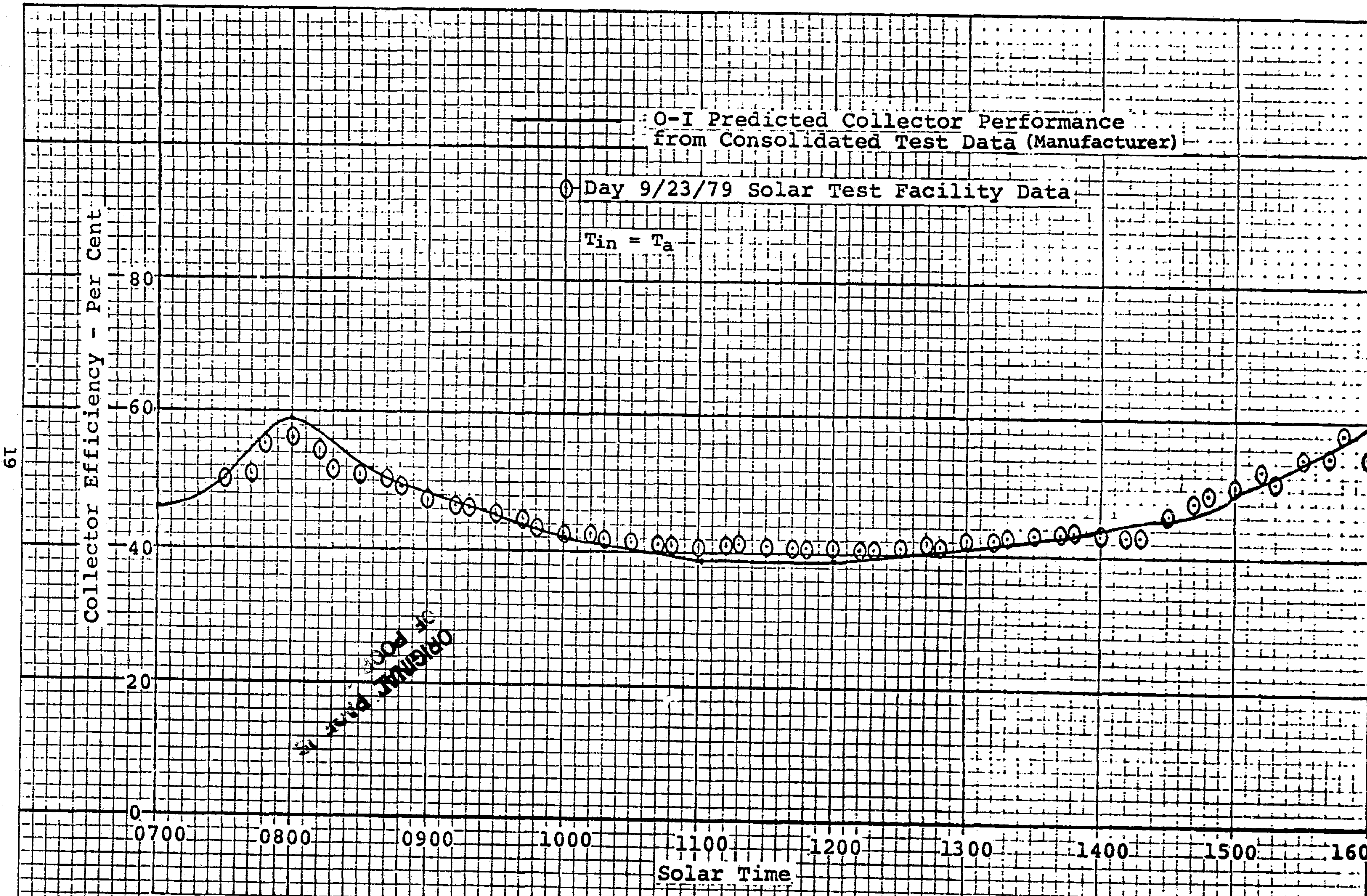

Figure 4. Sunpak SEC-601 Performance Compared to Predicted Performance

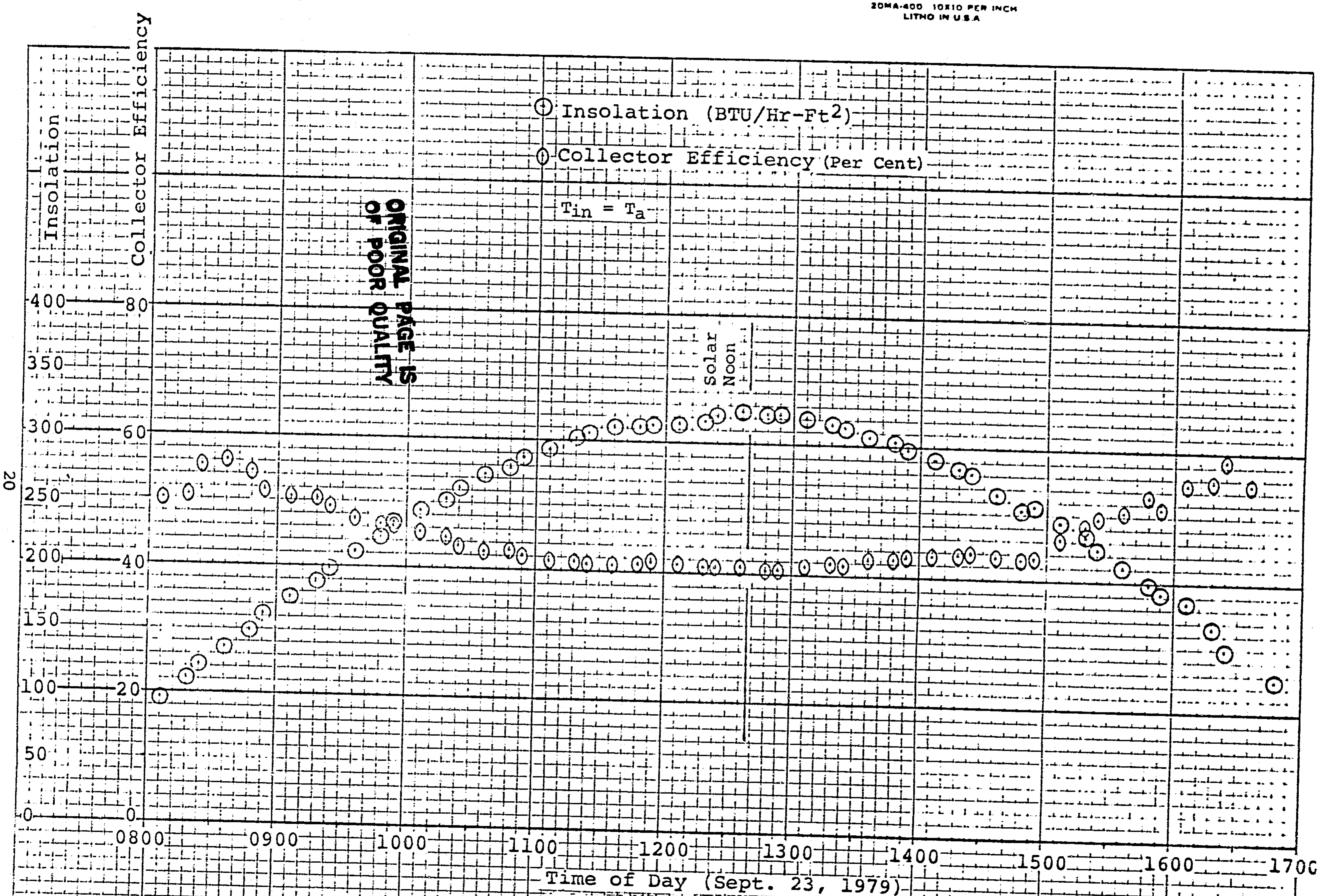

Figure 5. Sunpak SEC 601 Collector Efficiency at Recorded Insolation Values Vs. Time of Day for 9/23/79

9/15/79

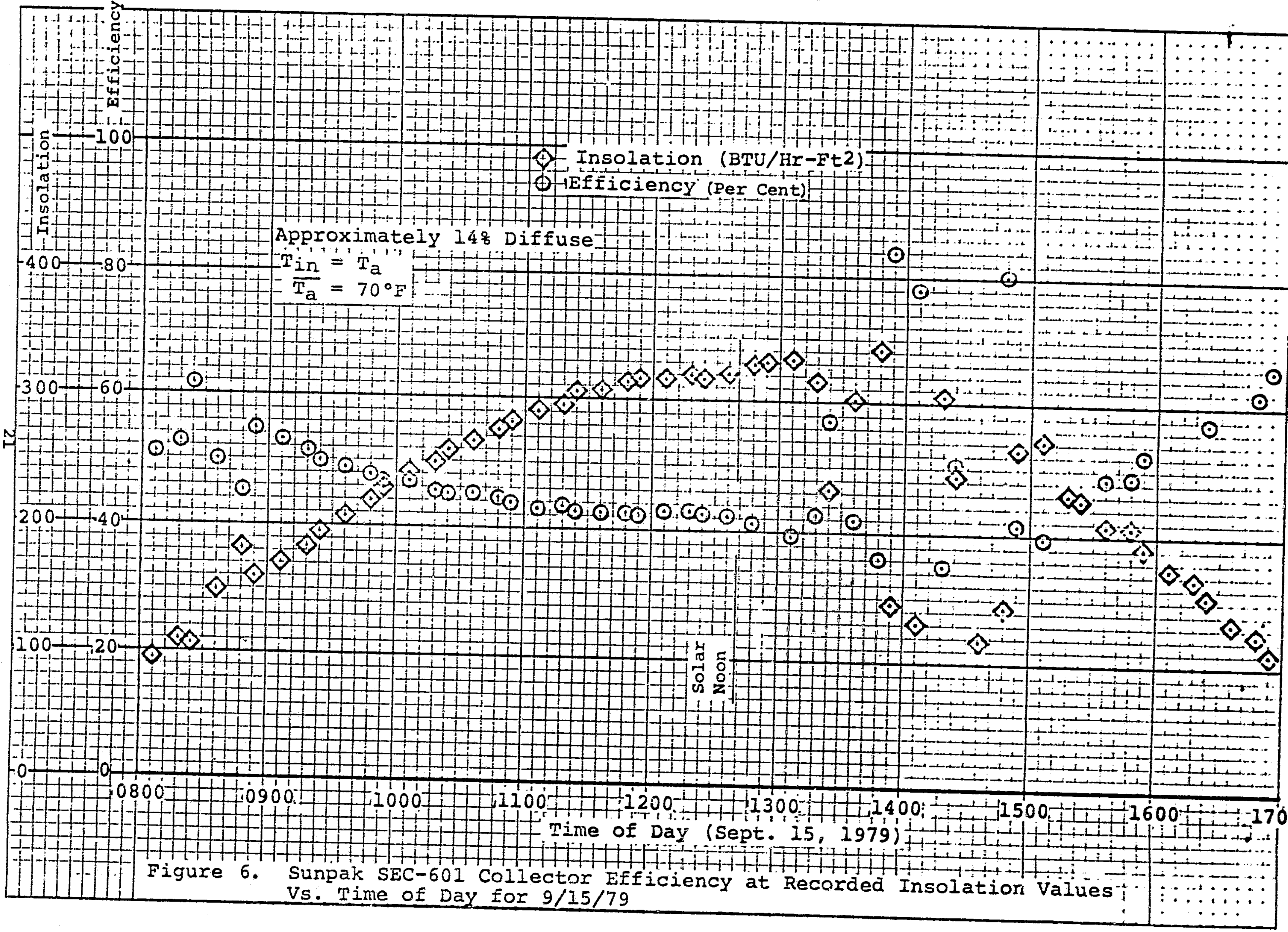

Figure 6. Sunpak SEC-601 Collector Efficiency at Recorded Insolation Values Vs. Time of Day for 9/15/79

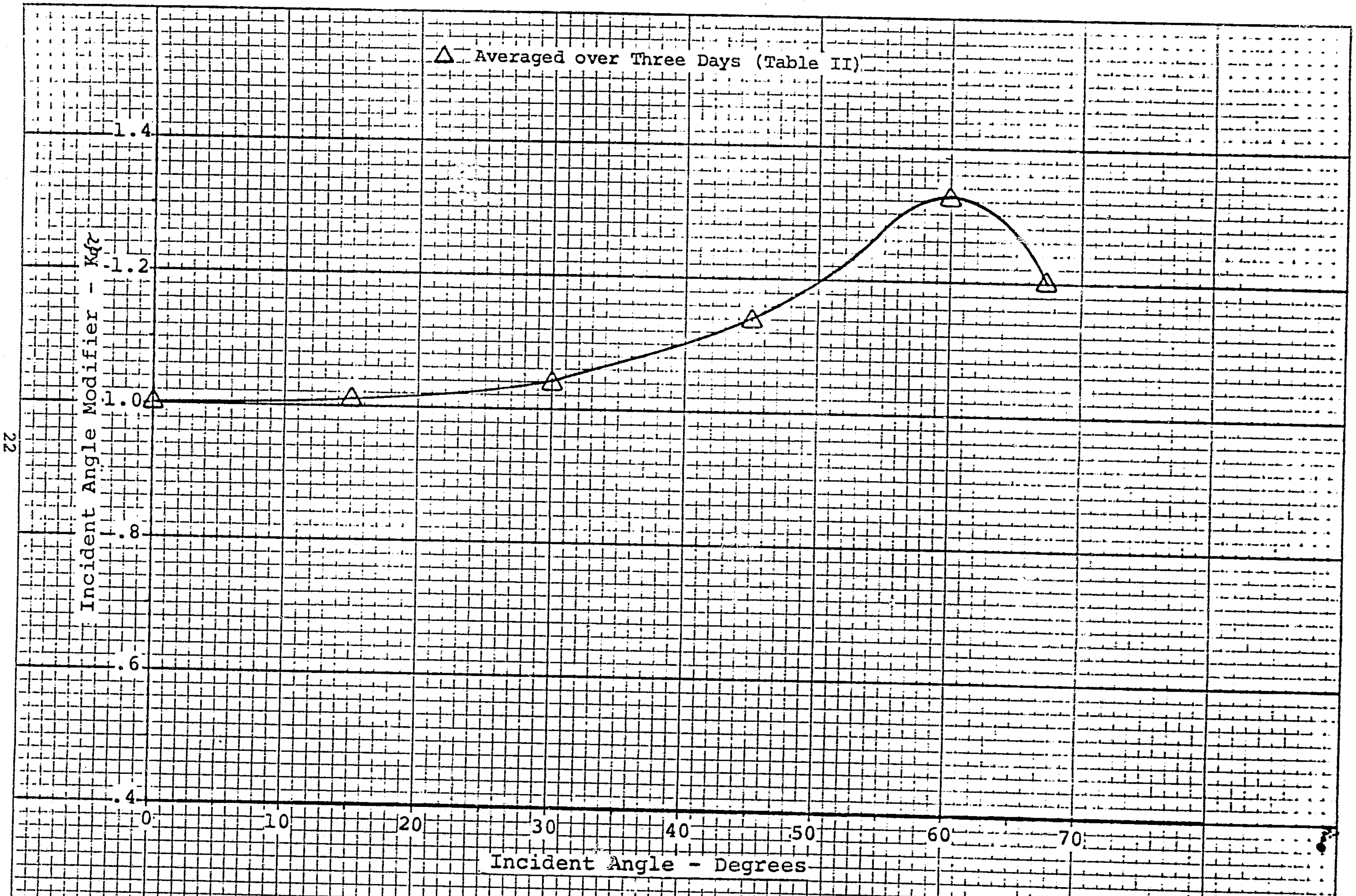

Figure 7. Incident Angle Modifier for the Sunpak SEC-601 Evacuated Tube Air Collector

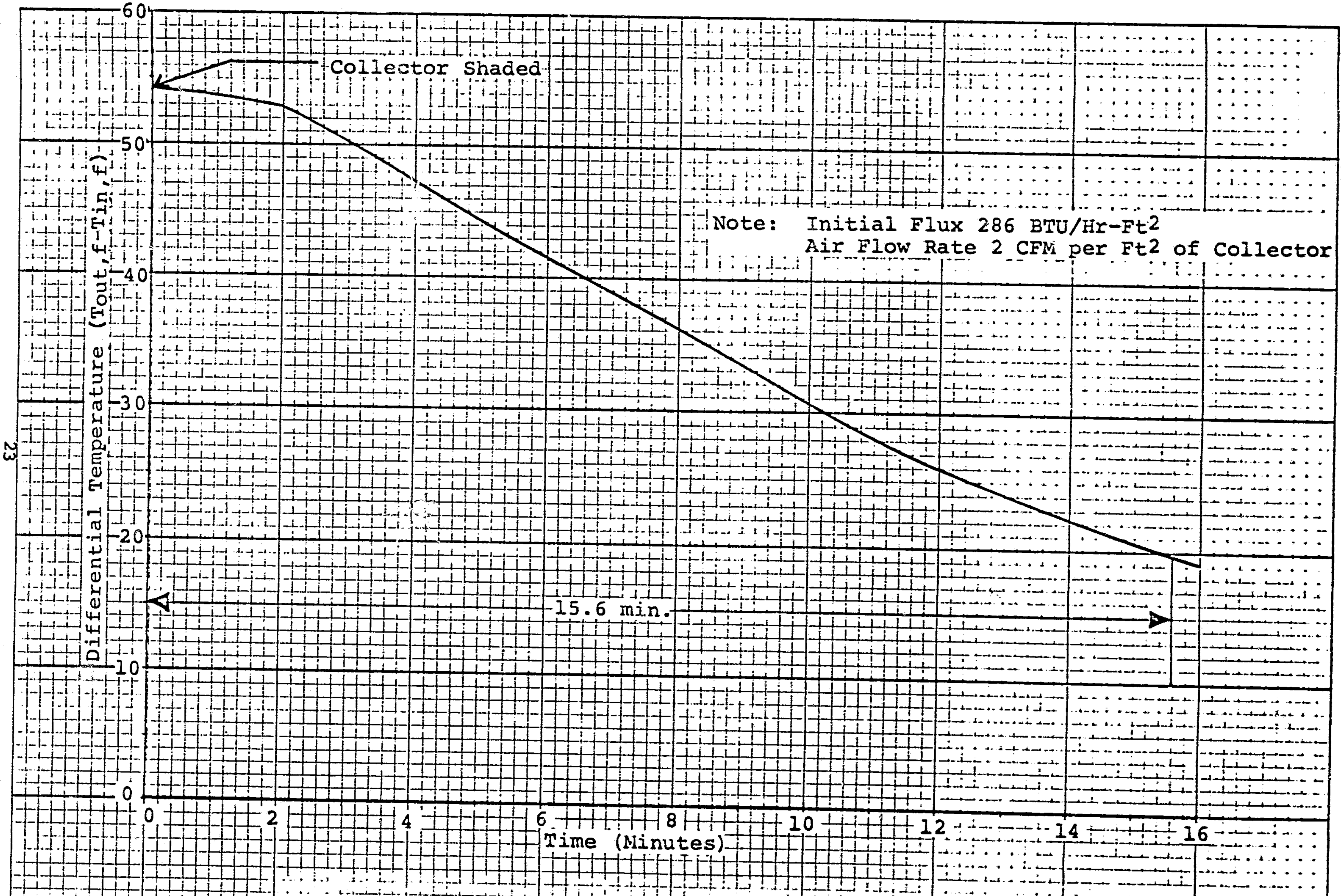

Figure 8. Time Constant Test for Owens-Illinois Sunpak SEC-601 Evacuated Tube Air Collector

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